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ABSTRACT

"Chaos" theory is a revolutionary new paradigm developed by scientists to study the behavior of natural systems. "Chaos" refers to the tendency of dynamic non-linear systems toward irregular, sometimes unpredictable, yet deterministic behavior. Major tenets of the theory are presented. The precedent for use of models developed in the natural sciences to model educational systems is discussed. Several examples of educational research using alternatives to the traditional linear model to study complex systems are presented. Finally, the implications of using the "chaos" model to study educational systems are discussed. It is probable that educational researchers will continue to rely on the linear model when the purpose is to study and predict simple effects. However, a model of the chaotic, yet deterministic, non-linear behavior of dynamic systems can contribute to the understanding of educational systems. The behavior of educational systems may turn out to differ from natural systems in some crucial ways, but the new paradigm offers a new way of looking at educational systems. (Author/SLD)

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"CHAOS" THEORY: IMPLICATIONS FOR EDUCATIONAL RESEARCH

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ABSTRACT

"Chaos" theory is a revolutionary new paradigm devoloped by scientists to study the dynamical, nonlinear, yet deterministic behavior of natural systems. In this paper its major tenets are presented. The precedent for use of models developed in the natural sciences to model educational systems is discussed. Several examples of educational research using alternatives to the traditional linear model to study complex systems are presented. Finally, the implications of using the "chaos" model to study educational systems is discussed.

Subject Descriptors: 1. "Chaos Theory" 2. A Nonlinear Model of Natural Systems 3. A New Research Paradigm

PURPOSE

The purpose of this paper is to describe the theory of "chaos" and to explore its implications for educational research. The term "chaos" was coined by scientists to refer to, the tendency of dynamical, nonlinear systems toward irregular, sometimes unpredictable, yet deterministic behavior. An excellent account of this revolutionary "new science" has been written by Gleick, a science reporter for the New York Times (1987).

RATIONALE

Social scientists have long been interested in adapting models originally developed to study the behavior of natural systems to the behavior of social systems. Perhaps the most notable example of this process is the information theory model, (Shannon & Weaver, 1949) first developed by a mathematician and later adapted by social scientists as a way to describe organizational behavior. According to Bateson (1972), "The technical term "information" may be succinctly defined as any difference which makes a difference in some later event."(pg. 381) The major tenet of information theory, derived from the Second Law of Thermodynamics, held that the universe has a tendency to become increasingly disorganized and to slide toward total collapse or entropy. Furthermore, this tendency held not only at the macro-level but at the micro-level as well. Thus researchers found this theory useful in studying phenomena as widely diverse as the ecology of a pond or the organization of

large corporations.

One important contribution of information theory was the development of systems analysis. General systems theory as conceived of by von Bertalanffy (1955), became a way of thinking about complex systems. Complex systems have been defined as "one made up of a large number of parts that interact in a non-simple way." (Simon, 1981; pg. 195). Thus, a change in one part of a complex system will result in changes throughout the whole structure. This principle holds true whether the complex system is an educational organization or the ecology of a pond.

SENSITIVE DEPENDENCE ON INITIAL CONDITIONS

The chaos model returned the physical sciences to the ideas of information theory. The notion that information is a difference that influences later events is closely related to a key concept of chaos theory. This concept is called "sensitive dependence on initial conditions" often called "the Butterfly Effect--the notion that a butterfly stirring in Peiking can transform storm systems in New York." (Gleick, 1987, pg. 8). Thus very minor disruptions in one part of a system can result in major changes in the system as a whole.

Weather forecasting is an exemplar of this concept. One meteorologist found that a very small change in initial conditions could result in widely different weather predictions. (Lorenz, 1962) Lorenz found that rounding a number from six decimal places to only three at a starting point produced weather patterns that eventually bore no resemblance to each other. Thus

the effect of a difference in the initial stage was multiplied until the point that it produced greater and greater differences.

Up to this time scientists were used to looking for regularities and disregarding small differences in results. For example, from the time of Galileo, scientists modeled the behavior of a pendulum as if it had regular periodic movements. In fact they were modeling a regularity that didn't exist. When scientists found evidence to contradict this assumption, they disregarded it, rather they regarded it as a little random noise somewhere in the system.

NONLINERARITY

Nonlinearity is a second noteworthy attribute of "chaos" theory. Scientists knew that nonlinearity existed, however, they were used to thinking of nonlinearity in dynamic systems as an exception. Turning to the example of the pendulum once more, scientists were used to disregarding friction and air resistance when studying the dynamics of pendulums. However, a few scientists were becoming aware that it is impossible to disregard those factors that produce nonlinearity. These scientists found that the solvable linear systems were the exception and that disorderly nonlinear systems were the rule.

However, this finding created a real problem because nonlinearity expressed relationships that were not strictly proportional. Scientists had developed few tools for dealing with nonlinearity. Models of linear systems can be manipulated, i.e., they can be taken apart and put together again. They are

solvable, while nonlinear systems were generally unsolvable.

THE CHAOS PATTERN

For a time it appeared that science had reached a dead end. If most systems were nonlinear,it meant that scientists lived in a highly disorganized world that was impossible to comprehend. However, as scientists began to experiment with simple equations, they began to understand better and better the nonlinear behavior of dynamical systems. Sensitive dependence on initial conditions implied that systems differed widely depending on their parameters. May, a biologist, developed a simple model based on the equation $y = rx(1-x)$ where y equals next years population, x equals this years population, and r equals the rate of growth. (1-x) keeps x in bounds because as x rises (1-x) falls. He used changes in the fish population of an imaginary pond to demonstrate the workings of his model. (May, 1976).

Using this equation, May experimented with hundreds of values for the parameter. The higher the parameter, the greater the degree of nonlinearity. When the parameters were low, the population reached and maintained a steady state. However, when the parameter was high, the steady state would break apart and the population would oscillate between two values. When the parameter was very high, the system began to behave unpredictably.

May was particularly interested in the critical boundary between a steady state and oscillation. He made a graph to demonstrate the behavior of the fish population. He found when

he set the parameter at 2.7, as the parameter passed 3, the line on the graph split in two. Then it began to split again and again. These splittings or bifurcations came faster and faster until the system reached a point of total disorganization or "chaos". Surprisingly in the middle of this chaotic behavior stable cycles began to return. Then it repeated the same pattern of bifurcations and it returned to chaos again.

This was an important finding, but, once again, it left scientists in a real quandary because it was assumed that this pattern was not universal. In the next few years, scientists from widely differing disciplines began to discover the same pattern. However, it remained for one scientist to make an even more important discovery, an organizing principle that fit the chaos model and described the behavior of many different kinds of systems.

UNIVERSALITY

Feigenbaum (1981), a scientists at the Los Alamos National Laboratory, was also interested in the behavior of nonlinear dynamical systems. The particular problem he was studying was the population of gypsy moths. He knew that in their life cycle there was a period of splittings, the splitting of two cycles into four cycles and so on. He knew that a slight change in the fecundity of gypsy moths could result in a change from a four year to an eight year cycle. Feigenbaum decided to try to determine the exact change in parameters that would result in these splittings.

While manipulating the parameters, he began to notice that the numbers began to converge, that is, the ratio of the second to the first was the same as the third is to the second and so on. Thus the numbers were not only doubling they were doing so at a constant rate. Feigenbaum began to realize there had to be some underlying principle of organization. Such a principle implies universality.

Using a trigonometric function on a hand-held calculator, he was amazed to find the same constant, 4.669 appeared from two very different equations, one simple and one complex. Then on a computer he calculated the constant to five decimal places, 4.66920, and even to 4.6692016090.

He began to understand that the constant expressed some kind of nonlinear relationship. For instance, a function might express the relationship between this year's and next year's population of gypsy moths. Using the equation $y=rx(1-x)$ and plotting the results on a graph would result in a parabola. Depending on the starting population, it could result in extinction, a steady equilibrium, an oscillating population, or chaos.

SCALING

Feigenbaum understood, at least in part, what was happening because geometric convergence meant that some thing in this equation was scaling. Scaling meant that some quality was being preserved while everything else changed. He intuitively visualized a picture of two small wavy forms and one big one,

that is, his dynamical nonlinear system would have the same patterns both at the micro and macro level.

Even more exciting for Feigenbaum was the growing suspicion that this scaling might be a universal property of nonlinear systems. Universality meant that different systems would behave identically. A discovery of universality would mean that all those techniques that looked at systems only in their steady state would have to be thrown out.

At about the same time a mathematician, Mandelbrot (1977), was studying cotton market prices since 1900. He discovered many of the same characteristics as Fegeinbaum had found in his study of animal populations. Mandelbrot was looking for patterns not at one scale or another but across every scale. He knew that changes in cotton prices did not fit the familiar bell shaped curve of the normal distribution. When he put the numbers into the computer, he realized that those numbers that did not fit the normal distribution, did fit from the standpoint of scaling. In other words the symmetry was one of large scales to small ones, that is, the pattern for daily prices fit perfectly the pattern of monthly prices.

This pattern of scaling is seen in many of the systems that make up the human body from the vasculatory system to the respiratory system. That is, the parts of these systems have the same structure as the whole of the system just as trees have limbs made up of branches. Until recently anatomists were used to studying these systems by breaking them down to their smallest

parts rather than looking at the system as a whole. However, a decade after Mandelbrot discovered the scaling pattern in economic systems, biologists began to note these same patterns in human systems.

STRANGE ATTRACTORS

Scientists identified another characteristic of systems called a strange attractor, the tendency of systems to revolve around a fixed orbit. For example, Feigenbaum found that no matter what the starting point, animal populations had a tendency to be attracted to the steady state or equilibrium point in the cycle.

When traditional time series are used to display data, it shows the characteristic chaos pattern of a system's steady state, then the bifurcations and oscillations between two points and finally chaos. When this same data is shown in phase space it is possible to view the trajectories of the system. Feigenbaum and others found that these trajectories traced a pattern around two points that formed a pattern much like a butterfly. He called these points strange attractors.

IMPLICATIONS

Chaos theory has had a profound effect on research in the natural sciences, but its impact has not been felt in educational research thus far. However, in the future it is probable that "chaos" will be used to model the dynamics of educational systems. The linear model has been a valuable tool for research purposes to describe the behavior of relatively simple systems.

However, most of the systems encountered in educational research are extremely complex. In a review of the book, "Chaos", Cronbach, (1988, pg. 46) makes the following observation;

> "Educational events have always been far more complex than our research methods, and the success of natural scientists in handling some of their messiest problems should inspire and perhaps instruct us."

Many of the questions that educators want answered are related to the impact of policies and curricular changes as they are implemented in local schools. Socio-economic and cultural effects create a dynamic, complex system as they interact with innovations at the local level. When traditional linear models are used to study such complex interactions, false conclusions can be drawn from the results (Cronbach, 1976).

In order to minimize error, researchers have used various strategies such as random assignment and control groups. However, in studying "chaos" phenomena, scientists have found that random error or noise may be an important element in shaping the structure of the system. "Sensitive dependence on initial conditions" implies that small errors are multiplied as they interact with other phenomena in dynamic systems. Thus the elimination of error may lead to erroneous conclusions. Dynamical systems by their very nature do not operate in a vacuum. As expressed by Glieck;

> "Predictability is one thing in a cloud chamber----it is something else altogether in the simplest tub of roiling fluid, or in the earth's weather, or in the human brain."(1987; pg.7)

He might have added, human behavior is one thing in a controlled

experiment and quite another in a real-life situation.

Educational researchers are accustomed to experimental paradigms that allow them to control the interaction between two or more variables that are of interest to their study. After the data is gathered, researchers organize the data to test for linearity. A finding of linearity implies that there is a relationship between these variables.

The scientists that developed the chaos model discovered that the linear or steady state of a system describes only a very narrow part of the systems's pattern. Thus it might be appropriate to use the linear model when the goal is to study only the steady state of a system. However, when the goal is to understand how the system functions as a whole, as is usually the case, a nonlinear model would provide a much more accurate picture.

The notion of scaling, i.e. that dynamical systems have identical structures at different levels would also have implications for research methodology. It implies that the scientist cannot fully understand parts without knowing the pattern of the whole. Reductionist models that allow researchers to study individual systems without relating them to one another might not be valid. If the educational system is conceived of as a hierarchy it is easy to visualize its structure as being self-similar at different levels.

If researchers find that educational systems fit the chaos model just as dynamical natural systems have, there would be a

major paradigm shift of the sort described by Kuhn (1970). It could revolutionize the way educational research is carried out. Researchers could make predictions based on a much wider range of information because they would take into account the way that changes in parts of a system interact to influence the system as a whole.

Educational researchers may never be able to develop a nonlinear model capable of collecting and analyzing the data generated by educational phenomena. However, educational researchers can use the chaos model as developed by physical scientists as a metaphor for viewing the behavior of their own complex, dynamical systems. There are precedents for educational researchers to adopt models for investigation derived from the physical sciences. The adaptation of information theory from physical systems to social systems is a prime example. Thus we find educational theorists, Immegart and Pilecki stating (1973; pg 30)

> "The term "system" can, therefore, be used to refer to a vast array of things from the smallest "whole" to the total universe. An atom, a cell, a plant, a man, a bird, a committee, a city, a nation, the world, and the universe are all examples of systems."

Immegart and Pilecki define a system as:

> " an entity composed of (1) a number of parts, (2) the relationship of these parts, and (3) the attributes of both the parts and the relationships."(ibid; pg.30)

Thus it is clear that an individual classroom is a kind of system that is part of the larger educational system that is, in turn, a part of an entire social system. If it were possible for

educational researchers to identify the many variables that go into shaping instruction in the typical classroom, then they could begin to develop methods capable of sorting out the influence of each of these variables that shape instruction.

A few models that attempt to deal with the complexity of educational systems have already been developed. The hierarchial linear model (HLM) developed by Bryk and Raudenbush (1986) is one such an attempt. The HLM was used to analyze the data generated by a study of the High School and Beyond (HSB) survey on the differential effectiveness of Catholic vs. public schools on math achievement. In the original study students were the unit of analysis while the effect of the classroom, a key sociological unit was ignored. Raudenbush and Bryk used the standard linear model with one major exception, the within-school regressions were allowed to vary across schools. They concluded:

> "HLM (hierarchial linear model) is a powerful tool that permits a separation of within-school from between school phenomena and allows simultaneous consideration of the effects of school factors not only on school means but also on structural relationships within schools." (1986, pg. 13)

Another attempt to understand dynamic social systems can be found in studies of the diffusion of innovations (Rogers, 1983). Diffusion researchers use techniques such as sociograms to trace the adoption of innovations. For example, Carlson (1965) analyzed the spread of modern math among school administrators in Pennysylvania and West Virginia. Rogers reports:

> Carlson conducted personal interviews with each of the thirty-eight superintendents who headed these school systems, asking each (1) in what year they had adopted

> modern math, (2) which other superintendents were their best friends, and (3) for certain other data. Modern math entered the local educational scene of Allegheny County by means of one school superintendent, who adopted in 1958. This innovator traveled widely outside of the Pittsburgh area, but he was a social isolate in the local network; none of the other thirty-seven administrators talked with him. The s-shaped curve did not take off until 1959-60 after a clique of six superintendents adopted; these six included the three main opinion leaders in the system. The rate of adoption then began to climb rapidly. There was only one adopter in 1958 (the innovator), five by the end of 1959, fifteen by 1960, twenty-seven by 1961, thirty-five by 1962, and all thirty-eight superintendents had adopted by the end of 1963 (1983, pg. 64-65).

The interview technique allowed Carlson to make visible the invisible path of the adoption of modern math in West Virginia and Pennsylvania. It revealed the pattern of the social network of school superintendents and identified "opinion leaders" as the vital variable that lead to adoption of the innovation. It would have been interesting to trace the adoption of modern math to the national level to find out if it displayed the characteristic "chaos" pattern that has been discovered in natural systems.

Researchers have also used ethnographic techniques of data gathering and analysis as means of capturing the complex patterns of interactions in educational systems. One of the most notable of these studies is the one carried out by Sinclair and Coulthard (1975) with 10 and 11 year old children, but later expanded to include children of all ages. Sinclair and Coulthard developed a rank scale analysis system for purposes of coding classroom discourse data. This system was similar to other linguistic rank scales based on the assumption that a unit at a given rank is made up of one or more units at the rank below. For example,

words are made up of morphemes that serve, in turn to make up a group and so on. The rank scale that makes up a lesson is composed of acts that make up moves that make up exchanges, and finally transactions that make up the lesson.

Another attempt to describe the structure of the classroom was carried out in San Diego by Mehan and his colleagues (Mehan, Cazden, Coles, Fisher, & Maroules; 1976) This study is particularly interesting because one of the researchers, Cazden, served also as the classroom teacher of the class involved in the study. Thus, the researcher became a participant of the culture that was being investigated. Mehan et. al. described a sequential organization of the lesson, consisting of an opening phase, an instructional phase and a closing phase. Each of these phases was subdivided into smaller units that revealed a hierarchal structure to the lesson. Thus it is possible to identify a pattern in which smaller units are nested in larger units.

CONCLUSIONS

It is probable that educational researchers will continue to rely on the linear model when the purpose is to study and predict simple effects. Indeed, this model has contributed greatly to our understanding of many educational processes. However, when used inappropriately, it can lead to a false picture of school effects. It is particularly unfortunate when erroneous results serve as a basis for formulating policies and programs at the local level.

Raudenbush and Bryk has expressed this problem in the following way:

> "Research on school effects has been plagued by both methodological and conceptual problems. In our view, the two are closely related. The available analytic models tend to limit conceptualization to what can be empirically tested through such models (1986, pg. 15).

Thus, we need research paradigms that broaden rather than limit our conceptions of the complex influences that interact in shaping educational outcomes.

Perhaps scientists' model of the chaotic, yet deterministic, nonlinear behavior of dynamic systems can contribute to our understanding of educational systems as well. It is entirely possible that the behavior of educational systems may turn out to differ from natural systems in some crucial ways. However, the nonlinear paradigm would still be valuable to researchers as a metaphor because it provides a new way of looking at educational systems. Such paradigm shifts have revolutionized scientific endeavor in the past and will continue to do so in the future (Kuhn, 1970).

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